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Crystal Testing

Oscillator crystals are nothing new. Technical applications for their piezo-electric effects have been known for 60 or 70 years. Their characteristics have been known about for just as long. Manufacture was and is constantly refined. Nevertheless, a crystal is still a relatively expensive component. And you don't throw it away when it's done the job it was made for. It can be used in an experimental set-up at frequencies which diverge by up to 0.5%, even with another upper harmonic. It may also be used in a filter or demodulator.

The pre-requisite is that all its characteristics are known. The article describes ways in which they can be measured. This then leads to some new types of application. I assume that the reader is informed about the basic characteristics of crystals, as they are explained in the catalogues of most reputable manufacturers. What follows below is what you won't find there.

1. INTRODUCTION

Everyone knows this effect. You introduce a crystal into a tried and tested circuit and find that the frequency generated does not correspond to the one printed on the crystal. This can be verified using simple frequency meters, which nowadays measure with greater precision than that with which crystals are manufactured.

So who is at fault, the user or the manufacturer? Probably both! The user, because he or she is using the crystal in a way which the manufacturer did not expect, and the manufacturer, because he or she has not printed enough data on the crystal.

There are certainly enough examples of this. There is a crystal in my DIY box which is simply marked "60.2 MHz". The manufacturer apparently wishes to remain anonymous, and perhaps with good

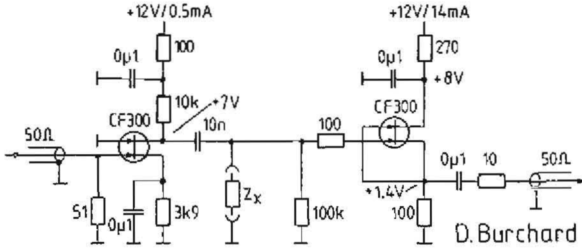

Fig.1:

Meaurement circuit for Impedances from 0 to app. 10kΩ; 50Ω Input and Output

reason. Another carries the description "6 MHz SWS". The abbreviation refers to a dealer who probably knows nothing else about the crystal. A third is referred to as "Valvo 18.000000". We can easily interpret this as 18 MHz (which is correct), with a comparison precision of 5 decimal places after the last digit written down (which is incorrect). It would actually mean that the tolerance was only 0.028 ppm. No manufacturer, however crafty, could promise that!

One example of a crystal marked with sufficient information is the following: TQ790516:216.631.25 range. First comes the code for the manufacturer, Telequarz (TQ). We then find that this is a crystal in an HC-45U housing (7...) in the ninth upper harmonic (.9...) with a comparison

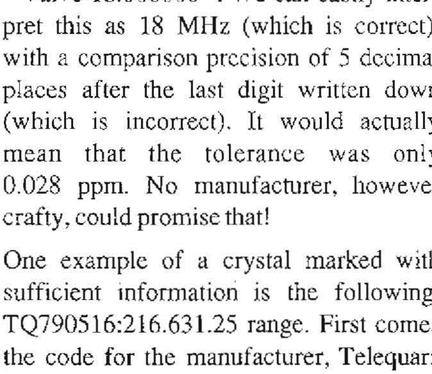

Fig.2: Impedance curve of a crystal Y: 5db/div; x: 25 MHz/div 0 ... 250 MHz

tolerance of ± 10 ppm (...05..) and TK of ± 7.5 ppm between -20 and +70°C (...16), which has series resonance at 216631.25 MHz. This is enough for the crystal to be used in accordance with the regulations. And there is hardly room for anything else in the small housing. If you want to use this crystal in a different way or to understand the cheap crystal with the inadequate description better, then you must do your own measuring.

2. CRYSTAL RESONANCES

Like any three-dimensional image, a crystal has more than one resonance. You can find any number of resonances, provided only that you make the frequency range of the investigation wide enough and select a sufficiently fine resolution. A suitable method is to measure the apparent resistance over the frequency range in question. Fig.1 shows a suitable measurement circuit, consisting of a power source and a source follower, which follows (1). It is wired into the signal path of a wobbler, network analyser or spectrum analyser with a tracking generator. For the TQ crystal referred to above, for example, you get an image like Fig.2. We are initially struck by a hyperbolic impedance

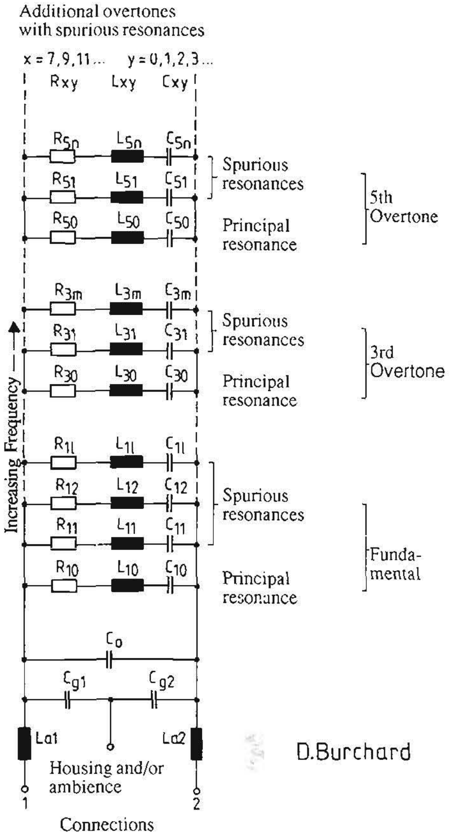

Fig.3: Complete equivalent circuit diagram of a Crystal

decrease, which in reality is a logarithmic hyperbola. It can be traced back to the capacity between the electrodes. The actual resonances of the crystal can be detected through small "swerves" in this hyperbola. This kind of thing is clearly visible at 24, 72 and 120 MHz, but can scarcely be made out at 170 and 217 MHz. The resolution is evidently not fine enough.

There are measuring instruments nowadays which can measure such curves in steps of 10 Hz. An expression of the frequency range of Fig.2 with a 0.1 mm. step width would be 2.5 km. long. So it is better to investigate each "jump" separately by reducing the sweep hub, once a general view has been obtained as per Fig.2.

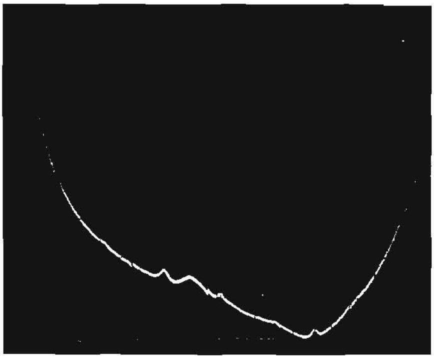

Fig.4: Appearance of a Zero Point in the Impedance Curve when long leads are used (scale division as Fig.2)

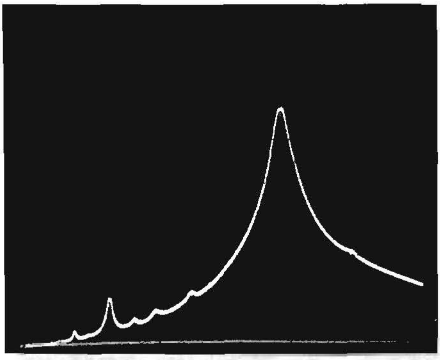

Fig.5: Compensation of electrode capacity generates a Parallel Resonance (here) atthe 7th Overtone (scale division as Fig.2)

There is thus a fundamental - this is the jump at the lowest frequency. Then follow the upper harmonics, each at an interval of about double the fundamental frequency. All of them have spurious emissions in their neighbourhood, as we shall see later. This gives the complete equivalent-circuit diagram of a crystal (Fig.3). Each resonance is represented by a circuit in series, R_{xy}, L_{xy}, C_{xy}. The capacity between the electrodes is referred to as C_0. Other capacities arise between the electrodes and the housing, which should usually not be neglected, and in addition the wires to the connections have a certain inductivity. The latter is obviously noticeable only in very long lines. For Fig.4, jumper wires 100 mm long were mounted as an extension at 10 mm. intervals, which created a series resonance with C_0 and C_g at 180 MHz. It can be concluded from this that L_{a1} and L_{a2} play no part in reasonable lengths of wire of under 10 mm., unless the frequency exceeds 300 MHz. At the moment, however, this is also the limit beyond which crystals are not available. It had, of course, already been reached 60 years ago with tourmaline crystals.

The representation of a series resonance is made considerably more difficult if there is a parallel low impedance of C_0. This is the case for all the higher upper harmonics. One way out is to compensate for C_0 by means of a parallel-wired coil. Its effect can be seen in Fig.5. The seventh overtone, for which compensation has been provided, is now clearly prominent, and the resolution can be markedly improved by reducing the sweep hub. The main resonance of the seventh overtone can be seen on the far left in Fig.6. All "satellites" to the right of it are spurious emissions. Now it is also clear that the resolution can not be increased any further using the broad-band wobbler. Its interference dispersion is several kHz, which is too wide. This means that steep parts of the curve are shown broken up and their more precise course or the minimum value (the series resonance) can not be made out.

3. MORE PRECISE REPRESENTATION OF RESONANCES

So a generator with a much narrower interference dispersion is needed; 100 Hz may be sufficient in many cases, 10 Hz always is. Such values can be found in signal generators which are provided for the measurement of high-quality receivers. This need not be the newest, most expensive model from one of the big manufacturers. What is required is the ability to modulate the frequency, with a lower limiting frequency as low as possible (1 Hz, 0 Hz are even better!), fine adjustability of the frequency and little drift, so that a meter can be connected up to determine the frequency. 10 Hz drift over a few seconds meets all requirements.

Old valve equipment from the surplus market with mechanical elements which are still operating smoothly can be modified relatively simply. The author has done this previously, using equipment from Rohde & Schwarz (SMAF type, made in 1954) and Eicke & Bemmerer (type SGU 702, made in 1965) with good results. A meter output was provided, electronic fine tuning was incorporated, and the double capacitors in the FM modulation path were

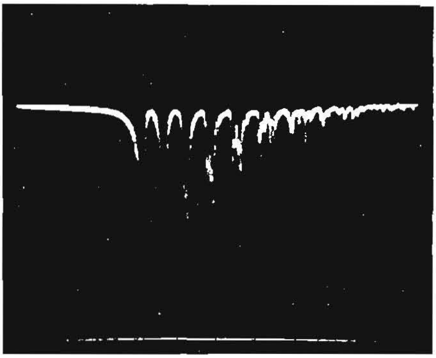

Fig.6: Main Waves and Spurious Emissions at 7th Overtone after Compensation

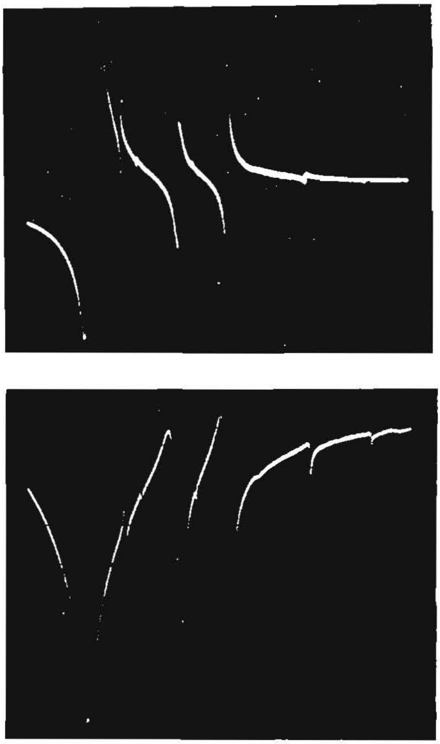

Fig.7: Principal and Spurious Resonances at Fundamental; (a)without compensation; (b) with compensation Y: 5dB/div; X: 30 kHz/div

considerably enlarged. However, the illustrations show the results obtained using a home-made signal generator, which can be modulated from DC and has an interference dispersion of about 50 Hz.

With such a generator and still rather a wide dispersion, we can obtain a good general view of the main resonances and their spurious emissions, shown here in Figs. 7 to 9 for the fundamental and the fifth and ninth overtones of the specimen TQ crystal. The spurious emission damping can be read off directly. Anyone not having a calibrated Y axis must change the generator voltage until first the principal wave and then the spurious emission coincide with the same screen line, and finally convert the results into dB.

The images shown in section a are obtained using uncompensated measurement. Here the parallel resonance can be seen just above the series resonance. It occurs at points where the imaginary part of the crystal series resonance impedance curve, in terms of quantity, is equal to the impedance of all C_0, C_g and external "load" capacities parallel to the crystal. The frequency is thus not determined through the crystal alone, but can be stretched rather far through external wiring. We do not need to determine it, because it can always be calculated from the equivalent data and the wiring. The images shown in section a also illustrate how measuring the series resonances without compensation is possible only for fundamentals and overtones of a low order. It is therefore a good habit always to measure using compensation. The criterion for correct compensation is a symmetrical shape for the series resonance curve in the vicinity of the resonance point, as can also be seen from the images in section b.

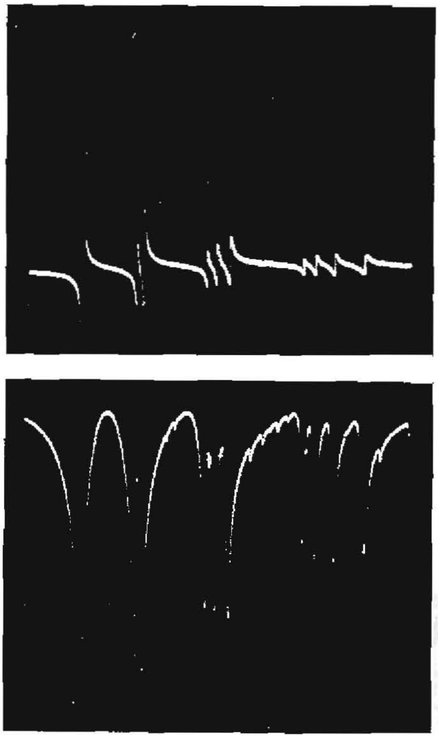

Fig.8: Principal and Spurious Resonances at 5th Overtone; (a) without compensation; (b) with compensation Y: 5dB/div; X: 20 kHz/div

The spurious emissions from the overtones occur at an increasing distance from the principal wave in groups of 2, 3, 4, etc. I have never yet found an explanation for this undoubtedly interesting behaviour anywhere.

4. MEASURING THE EQUIVALENT DATA

The electrode capacity, C_o, and the housing capacities, C_g, can be measured using

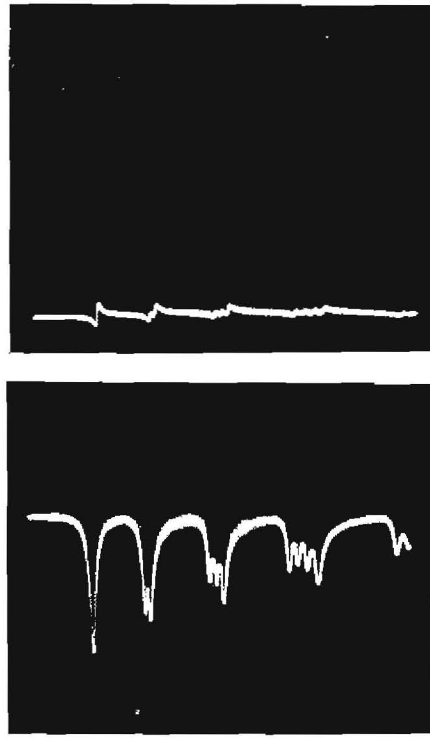

Fig.9: Principal and Spurious Resonances at 9th Overtone; (a) without compensation; (b) with compensation Y: 5dB/div; X: 20 kHz/div

any capacity measuring equipment with a sufficiently high resolution. The author uses a Marconi TF2700 universal Wheatstone bridge, which requires a measuring frequency of 1 kHz. This low frequency ensures that a crystal resonance is never measured when excited, and thus incorrectly. For capacity measurement, a crystal has three connections: the electrode leads and the housing. So three measurements must be carried out, each involving two connections linked to one another, so $C_x = C_{g1} + C_{g2}$, $C_y = C_o + C_{g1}$ and $C_z = C_o + C_{g2}$ can subsequently be determined. A simple calculation then gives:

$$C_o = \tfrac{1}{2}(-C_x + C_y - C_z) \quad (1a)$$

$$C_{g1} = \tfrac{1}{2}(C_x + C_y - C_z) \quad (1b)$$

$$C_{g2} = \tfrac{1}{2}(C_x - C_y + C_z) \quad (1c)$$

Because of the symmetrical structure, one would expect that $C_g = C_{g2}$, and in the majority of cases this is correct. However, discrepancies do occur if, for example, the crystal is mounted slightly askew. The following capacities were measured for the test crystal: C_o = 4.1 pF; C_{g1} = 0.6 pF; C_{g2} = 0.7 pF.

With regard to the spurious emissions, the first point of interest is the spurious emissions interval, which has already been determined. Then we may perhaps wish to note the frequency intervals to the principal resonances. They can be read off directly, e.g. from Figs. 7 to 9. As a rule, we shall not want to know the L_{xy} and C_{xy} values of the spurious emissions. If we do, we proceed in exactly the same manner as described below for the principal resonances.

The desired resonance is brought into the centre of the screen by means of transmitter tuning, and the dispersion is reduced until an image corresponding to Fig.10 or Fig.11 is obtained. The symmetry indicates that the compensation has been set correctly. A suitable X frequency must be selected, so that the forward and reverse cycles coincide (splitting, as later in Fig.21, is only just permissible). The meter connected to the transmitter will eliminate the frequency variation by averaging if the gate time is long enough (e.g. 1 s.). This can easily be subsequently verified in that sequential meter displays vary by only a few Hz. The horizontal line in Fig's.10 and 11 corresponds to an impedance of 100Ω. If a 100Ω resistance is wired up instead of Z_x and another channel of the oscillograph is made to coincide with this line and is left there unaltered, we have this permanent reference line.

With the desired resonance exactly in the centre of the screen, the value is now read off from the meter. This gives the series resonance, f_{xo}. The +3 dB bandwidth has to be determined next. It is read off at the calibrated axes, or the transmitter voltage is reduced by 3dB and displaces the tuning in such a way that now the curve goes through the point on the screen where the

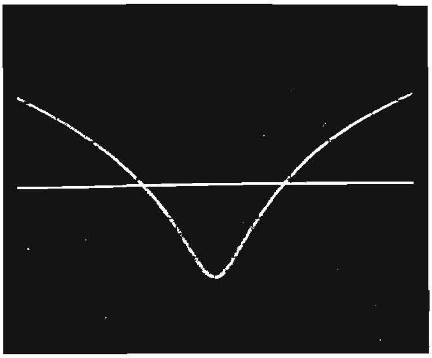

Fig.10: Image during measurement of Fundamental Y: 5dB/div; X: 20 kHz/div

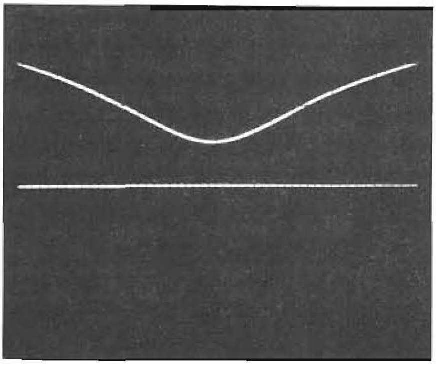

Fig.11: Image during measurement of 9th Overtone Y: 5dB/div superimposed 100Ω line; X: 1 kHz/div

minimum value was previously. This gives two frequency values to be read off, their difference being the band width, fxo. The third value required is the series resonance resistance. By comparison with the 100Ω line and the calibrated Y axis, we obtain the factor in dB: -12 dB as regards Fig.10 or +6dB in Fig.11. The resonance resistance, R10, is thus 25Ω, while R90 is obtained as 200Ω. If there is no calibrated Y axis, the simplest method is to replace the crystal by a trimming potentiometer, set it in such a way that the line arising coincides with the valley point of the previous resonance curve, and then measure. Varying the transmitter voltage until the valley point coincides with the reference line also gives a result. We can then carry out the calculation:

$$Q_{xo} = f_{xo} / f_{xo} \qquad (2)$$

$$Lxo = \frac{Qxo \cdot Rxo}{2 \cdot \pi \cdot f_{xo}} \qquad (3)$$

$$C_{xo} = \frac{1}{2 \cdot \pi \cdot f_{xo} \cdot Q_{xo} \cdot R_{xo}} \qquad (4)$$

The value measured for the sample crystal, together with the equivalent data calculated from it using equations (2)...(4), is shown in Table 1. By comparing the data with those from the manufacturer (2), we can recognise that they are all within the given range. The obvious conclusion is that there is no basic variation in the manufacture of basic crystals and overtone crystals, at least not with this structure. And there is thus nothing to prevent the crystal's being used at another resonance.

A comparison of the f_{xo} frequencies measured discloses that the overtones are not distributed harmonically - a fact mentioned in every textbook. But what is not mentioned is that they are all distributed harmonically in relation to a fictitious keytone, which here is 24.070 MHz. If this is taken into account, the overtones can be calculated with an error amounting to only a few tens of ppm. There is an obvious explanation. The electrodes charge the crystal and lower its frequency (here by 1,255 ppm). This effect is used for the fine tuning of the frequency, in that metal is deposited until the rated frequency is reached. This influence is at its greatest for the fundamental. The batches of metal are located at the maximum amplitudes. The overtones can not be influenced so easily, because several maximum amplitudes lie within the crystal's interior. The fictitious fundamental is calculated by halving the frequency interval for two adjacent overtones.

		Fundamental x = 1	3. Overtone x = 3	5. Overtone x = 5	7. Overtone x = 7	9. Overtone x = 9	
Measured value	f_{xo}	24,040.5	72,211.6	120,356.4	168,493.4	216,629.6	MHz
	Δf_{xo}	1,40	2,60	2,80	4,20	4,20	kHz
	R_{xo}	25	50	65	130	200	Ω
Calculated value	Q_{xo}	17000	28000	43000	40000	52000	–
	L_{xo}	2,8	3,1	3,7	4,9	7,6	mH
	C_{xo}	15,6	1,6	0,47	0,18	0,07	fF

Table 1

5. MEASUREMENT OF TEMPERATURE BEHAVIOUR

The crystal oscillator has such a small thermal capacity that it very rapidly adopts the temperature of the housing due to radiation. If the housing in the measurement circuit is treated with a cooling spray or with hot air, the resonance can be seen to drift, and can also be measured by trimming the frequency at the centre of the screen. The cooling spray generates snow on the housing. If the snow melts, the temperature is pretty close to 0°C. A less well-defined temperature point lies at 50°C, "measured" by testing with a finger after heating. If the temperature is still higher, then you will have to move your finger away at once. At 50°C a brief contact is already possible. Anyone wanting more precise information will have to put a thermometer over the crystal or use a digital thermometer.

The two symmetrical temperature test points located at 25°C make it possible to determine whether the crystal was manufactured for a wide temperature range (-20 to +70°C) or a narrow one (0 to +50°C), or for a specific temperature (thermostat operation 60...90°C). The crystal catalogues usually give temperature behaviour curves which allow the three cases to be distinguished from one another. Then again, there are examples for which the frequency decreases below and above 25°C. This involves, not a thermostat crystal for 25°C, but a BT cut. Many cheap manufacturers prefer this cut for frequencies of 15...30 MHz, because the crystal is thicker than for an AT cut, and so easier to produce. The disadvantage is a considerably higher TK, which restricts use to the less critical cases, e.g. micro-processors.

6. CHANGING THE RESONANCE FREQUENCY

This procedure is referred to as "stretching the crystal", and is considered as being difficult and possible only to a small extent. This is definitely wrong. Later, we shall make the acquaintance of circuits which allow considerable "stretching". It is even true that the natural limit for stretching is at fairly high frequencies, because spurious resonances always arise there. The stretching procedure would have a point of discontinuity!

Stretching is always required if a circuit has to supply a more precise frequency than is given by the manufacturer's tolerance for the crystal. Otherwise, it would not be possible to align a frequency standard to 0.01 ppm ($1 \cdot 10^{-8}$) using a crystal with an accuracy of adjustment of 2 ppm.

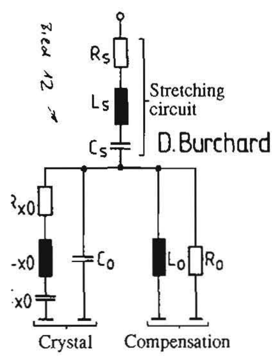

Fig.12: Universal stretching circuit for Series Resonance Crystals

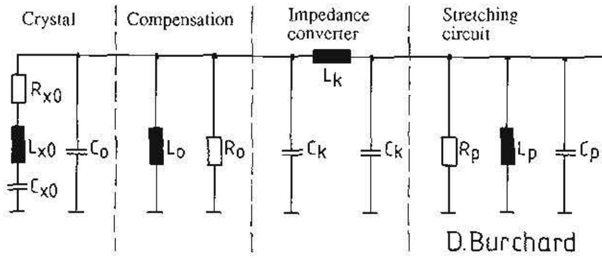

Fig.13: Universal Stretching Circuit for a Parallel Resonance, conversion of Series Resonance into Parallel Resonance

Fig.12 shows a general "stretching circuit" for series resonance. It consists of a second series resonance circuit (R_s, L_s, C_s), which is wired up in series with the crystal. For symmetrical stretching characteristics, the crystal must be compensated for. Initially, the stretching circuit must have the same resonance frequency as the crystal. Detuning them leads, in accordance with equation (5) below, to the displacement of the total resonance by Δf_z. In practise, the possible Δf_z changes are still very small, as against the crystal resonance, f_{x0}; there is a simple interrelationship:

$$\Delta f_z = f_{zo} \cdot \frac{C_{xo}}{2} \cdot \left(\frac{1}{C_s} - 4 \cdot \pi^2 \cdot f^2_{xo} \cdot L_s\right) \quad (5)$$

Thus, if Ls is missing from the circuit, only a stretching capacitor is wired in series, and the equation is simplified to:

$$\Delta f_{zc} = f_{x0} \cdot \frac{C_{xo}}{2 \cdot C_s} \quad (5a)$$

Frequencies can then only be increased.

If, on the other hand, the circuit contains only a stretching coil, then the equation which applies is:

$$f_{zL} = -2 \cdot \pi^2 \cdot f^3_{x0} \cdot C_{x0} \cdot L_s \quad (5b)$$

and frequencies can only be reduced.

The network theory states that a network made up of n reactive components has n - 1 resonance points. The crystal alone has three reactive components (C_{x0}, L_{x0}, $C_0 + C_g$), and thus two resonances; namely, the series resonance, which is always used here, and the parallel resonance, which is just above it, without compensation. If L_0 is introduced, a further resonance arises. It can be seen from Fig.7 that the original (natural) parallel resonance is displaced to considerably higher frequencies, whilst a new series resonance arises below the existing value. Two further series resonances arise above and below the existing parallel resonance points. Without further measures, their resonance resistance can be below $R_{x0} + R_s$, and an oscillator can be excited at one of these resonances. This can be remedied by reducing R_0. This resistance should initially represent the losses from L_0. If it is artificially increased, the parasitic series resonances are dampened.

A universal stretching circuit for the natural parallel resonance of a crystal does not exist, because this parallel resonance comes into being only through the interaction of further components and is not a characteristic of the crystal. However, by converting the impedance it is possible to convert a series resonance into a parallel resonance. The best-known impedance converter would probably be a λ/4 long

piece of coax cable. But there are also solutions using discrete structural elements. Fig.13 shows one such. Its conversion equation is:

$$Z_{in} \cdot Z_{out} = \frac{L_k}{C_k} \quad \text{when } L_k \cdot C_k = \frac{1}{\omega^2_{x0}} \qquad (6)$$

The impedance curve of the compensated crystal is thus inverted. A parallel-wired parallel stretching circuit acts in a similar way to the series circuit in Fig.12. The circuit is relatively complicated, even if some components are combined (C_0 and C_k, or C_k and C_p). Although this is a solution which satisfies the purists, the circuit is nevertheless very seldom used. So the calculation formulae for it will be omitted.

It is frequently sufficient to allow the current in a series circuit to flow through a resistance so as to obtain something like a parallel resonance. This frequently happens with uncompensated crystals which are under capacity load. We have a further example in Fig.18.

7. APPLICATIONS

There are a great many circuits for crystal oscillators in the literature. There is no space here to describe or evaluate them. I shall therefore limit myself to three specimen circuits, which are particularly good illustrations of the above remarks. All three use compensated crystals. To complete the picture, it should be explained that, in addition to a parallel coil, such compensation can also be provided by a capacity equal to C_0, which is powered by a counter-phase voltage. You need amplifiers with a counter-phase output or with a differential input, and solutions using differential transformers and bridge circuits are also conceivable. In any case, increasing attention must be paid to this problem as the frequency rises.

The next question is whether the crystal housing should be connected somewhere. The capacities between it and the electrodes are not negligible. Earthing is a good solution when one electrode is already earthed anyway or when the two are connected through earthed capacitors. If you decide not to connect up the housing, any foreseeable earth contact must also be avoided. An intermittent contact between the crystal housing and the earth surface of the printed circuit board can cause unattractive effects.

The circuit in Fig.14a is a crystal-stabilised phase circuit for a quadrature demodulator. This type of FM demodulation appeared on the scene with integrated circuits and requires a parallel resonance for two reasons. The circuit is powered from a

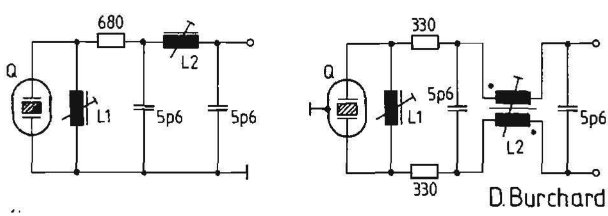

Fig.14: Crystal-Stabilised Parallel Resonance Circuit for use in an FM Quadrature Demodulator
(a) Asymmetrical, NE604
(b) Symmetrical, TDA1576

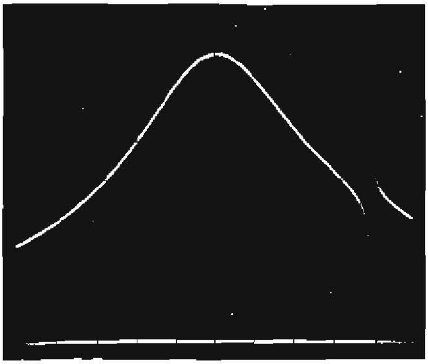

Fig.15: Fundamental Crystal Parallel Resonance generated in a circuit as per Fig.14. Y: linear, 0 line superimposed X: 10 kHz/div, average frequency 24040.4 MHz

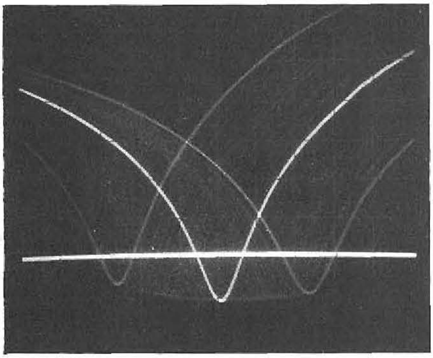

Fig.17: Operation of Fig.16 circuit Y: 5dB/div, 100Ω line superimposed X: 5 kHz/div, average frequency 24053 MHz

source which can not be subjected to whatever load you wish, and the input of the phase monitor requires a sufficiently high voltage. A circuit in series resonance would provide the same phase displacement in itself, but is ruled out for the reasons specified above. Naturally, there are many types of circuit which are also in operation somewhere. The circuit shown here is a "precise" solution to the problem.

The crystal compensated with L1 is taken to a sufficiently high band width, using a fixed resistance. This series resonance is

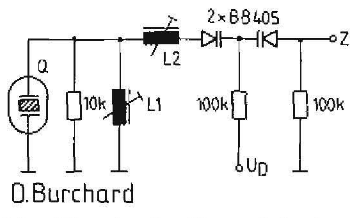

Fig.16: Circuit of a Crystal Series Resonance which can be electronically stretched

converted into a parallel resonance at 25 kHz using an impedance converter. There is thus a hump interval of 25 kHz in the quadrature demodulator and a useful linear band width of app. 15 kHz. The resulting parallel resonance can be measured using a circuit as per Fig.1. Fig.15 shows the measurement curve. An (inverted) secondary resonance can also be seen here, which lies outside the operating range. Many integrated quadrature demodulators need an asymmetrical structure. The part circuit shown in section a of Fig.14 is to be used in this case. Others, such as the well-known TDA 1576, require a symmetrical circuit, as represented by the part circuit in section b. The average frequency coincides with the series resonance frequency of the crystal. In practise, the two coils are tuned in such a way that the average frequency can be changed to a slight degree using L2 (but exceeding the tolerance of the crystal), whilst L1 ensures the linearity alignment.

The circuit in Fig.16 shows a resonator which, although crystal-stabilised, can still

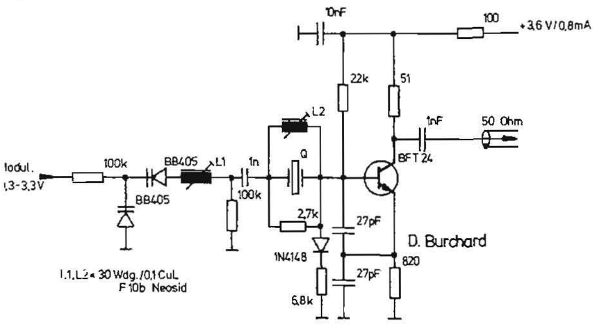

Fig.18:
FM Oscillator circuit,
Frequency 24053 MHz,
Dispersion ± 12.5 kHz

have its frequency varied to the extent of ± 500 ppm. It is used, for instance, in an oscillator which has to be "connected" to a considerably more precise standard frequency, or for fractional detuning, in a system which is otherwise digitally operated and does not allow for sufficiently fine frequency steps.

The inductivity, L1, compensates the crystal, the 10kΩ resistance dampens unwanted serial resonances, L2 and the capacitance diodes form the stretching circuit. The impedance curve can be measured at output Z as per Fig.17. For

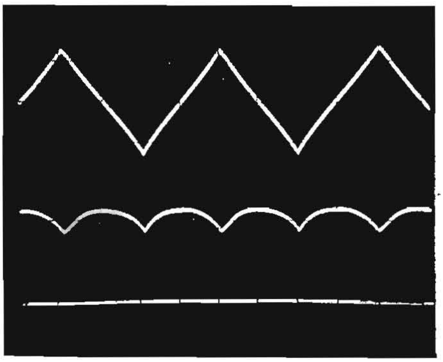

Fig.19: Modulation quality of Fig.18 circuit
Y1: 10 kHz Dipersion/div
Y2: 50% AM/div, zero line of rectifier superimposed
X: 0.5ms/div

this option, a DC voltage was fed into U_D, and a square-wave AC voltage was then superimposed on it for maximum frequency variation. During the exposure time, the square-wave voltage was slowly turned down to zero. The almost symmetrical detuning and the very high constancy of the resonance resistance can be recognised. The latter is naturally higher than that for the crystal alone, as is shown by a comparison with the 100Ω line, because the loss resistance of the stretching circuit is added. The resonance curve itself is markedly asymmetrical. The reason for this is that the capacity curve of the C-diodes plotted against the voltage does not match equation (5). It is not hyperbolic, but is more in accordance with the equation $C = C_0 (U + U_D)^{-m}$; U_D is about 0.6V and m is between 0.3 and 0.7, depending on the manufacturing process. The non-linearity of the frequency variation, restricted in this way, can be almost compensated for by slightly detuning L1. Of course, the C_0 compensation of the crystal is no longer correct. So in practise the linearity is set using L1 and the average frequency desired is set through L2.

The third circuit, Fig.18, represents the oscillator circuit of an FM transmitter, which was developed for scientific purposes. After quadrupling, it supplies wide-

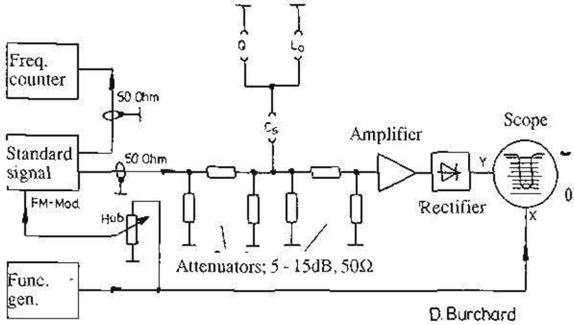

Fig.20: Simple Crystal measurement circuit

and FM over the standard radio range. Here the series resonance of the crystal is converted into a parallel resonance using an input capacitance, making the average frequency 12.5 kHz higher. In other respects, the circuit is largely the same as the one in Fig.16. However, the sequence of the components in the oscillation circuit is slightly altered, and a modulation input and a 50Ω output are created using a transistor.

The question of earthing the crystal housing arises again here. The author decided in favour of insulation and for safety reasons covered the crystal with a heat-shrinkable tube before assembly. Fig.19 testifies to the good quality of the modulation. According to the oscillator, the synchronous amplitude modulation fraction is only 15%, and largely disappears in the two subsequent doubler stages. The frequency modulation is noticeably linear, although the modulating voltage uses almost the entire operating voltage range. Here again, the precise frequency is set using L1 and the linearity is set using L2.

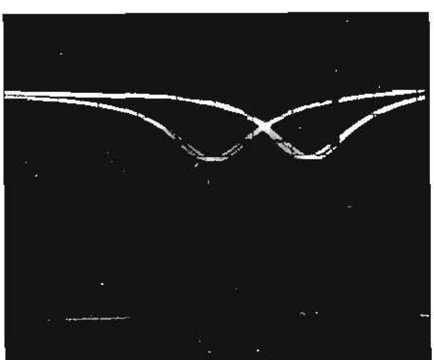

Fig.21: Screen Photo: Crystal Measurement using Fig.20 circuit and hand-written special scale
Y: 0.... ∝Ω, 0Ω superimposed
X: 2 kHz/div

8. IT IS EVEN SIMPLER TO MEASURE THE CRYSTAL

It should be remembered that a crystal with a series capacity, C_s, has the same series resonance as the same crystal in parallel resonance with a parallel capacity where $C_p = C_s$. So if the parallel resonance can also be measured as a series resonance, there is no longer any need for a measurement circuit as per Fig.1, suitable for measurements even in the kΩ range. Thus a considerably simplified circuit, as per Fig.20, is conceivable.

Here the crystal is mounted between two attenuators, which are there to ensure that the generator and amplifier see constant system resistances. Where the crystal is mounted, the impedance is 25Ω. The amplifier can consist of a wideband gain block. It is intended to compensate for the losses in the attenuators and simultaneously to add so much amplification that a simple rectifier can supply enough output voltage for an oscilloscope. The type of rectification and the curvature of the characteristic lines are of no importance. They are "calibrated into" the display on the oscilloscope. Only the same adjustment range (V/div.) must always be selected there.

The "calibration" is done with a felt-tip pen on an overhead film in front of the screen. The zero line is set on the oscilloscope without any generator voltage. The generator voltage is then turned up until the amplifier is well modulated but still in the linear range. Both the lines visible on the screen are marked, one as 0Ω, the other as ∞Ω. If we now switch in resistances of 10, 20 and 50 one after the other up to 500Ω, we obtain a calibrated Y scale. Intermediate values are estimated later or determined by means of substitution.

The procedure for measuring the resonance of any crystal is as follows:

→ Set the approximate frequency
→ Set the zero line without generator voltage
→ Increase generator voltage until the line is reached
→ Insert crystal and a short-circuit instead of C_S
→ Trim generator frequency to principal resonance
→ Insert compensation coil and adjust to best symmetry
→ Keep the resonance in the middle of the screen and read off the series resonance frequency on the meter
→ Read off the resonance resistance
→ Insert known stretching capacitor, C_S
→ Bring resonance to middle of screen again, read off the frequency and calculate the stretching frequency

The process is illustrated in Fig.21. The "graduations" in Ohms can be vaguely recognised in front of the screen, and a 0Ω line is also superimposed. The line is reached outside the resonance to be measured. During the exposure, the previously short-circuited 5pF stretching capacitor is switched in, and the resonance jumps from the middle of the screen to a value app. 5 kHz higher. The resonance resistance of app. 65Ω remains constant while this is happening, because of the compensation. This picture was taken with the specimen crystal on the fifth overtone.

Two defects in the image in Fig.21 require some explanation. An additional resonance can be seen very faintly at +7 kHz. This arises while the stretching capacitor is being reversed due to the switching capacity. Then a pronounced split can be seen in the curve between the scanning and the return passes. This is due to the increased recording speed. In order to ensure a certain basic brightness for the screen, so that the scale could be seen on the film, the X voltage was selected to be ten times as high as was necessary. So for 90% of the time the electron radiation falls on the glass wall of the valves and generates secondary electrons there. These reach the

screen and generate a diffuse brightening.

The equivalent data are calculated using somewhat re-modelled versions of the formulae already given above:

$$C_{x0} = \frac{2 \cdot C_{zC} \cdot \Delta f_{zC}}{f_{x0}} \qquad (7)$$

$$L_{x0} = \frac{1}{8 \cdot \pi^2 \cdot f_{x0} \cdot C_{zC} \cdot \Delta f_{zC}} \qquad (8)$$

The spurious emissions interval is obtained by measuring the resonance resistances of the spurious emissions and converting them into dB:

$$NWA/dB = 20 \log \frac{R_{xy}}{R_{x0}} \qquad (9)$$

It should be mentioned here that this type of crystal measurement is not according to standard (DIN 45105), but against this is considerably simpler. No special measuring head is required, no compensation branch and no phase meter. I see a further advantage in the fact that the capacities C_{g1} and C_{g2} can be taken into account in unambiguous manner by the single-ended crystal. If the housing is earthed, C_{g1} is parallel to C_0 and C_{g2} is short-circuited.

9. LITERATURE

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